A New Instrument for Testing Charge-Sign Dependent Solar Modulation

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Abstract. **For the purpose of understanding recent cosmic ray measurements in the energy region below 10 GeV it is important to obtain a good knowledge of the charge-sign dependent modulation caused by interplanetary magnetic fields. Existing three-dimensional time-dependent models of the heliosphere can be constrained further using series of measurements of the low-energy cosmic ray fluxes over the course of a solar cycle.**

Following the measurements of the positron fraction from AESOP in 2006 and 2009, we present a new light-weight spectrometer which is under construction in Aachen for measuring proton, positron and electron fluxes up to 5 GeV. The spectrometer consists of a permanent magnet, a transition radiation detector and a scintillating fiber tracking detector with a total weight of approximately 30kg. It is intended to be launched with a stratosphere balloon in 2010 as part of the German-Swedish Balloon-borne Experiments for University Students (BEXUS) program.

Keywords: **PERDaix low-energy electrons**

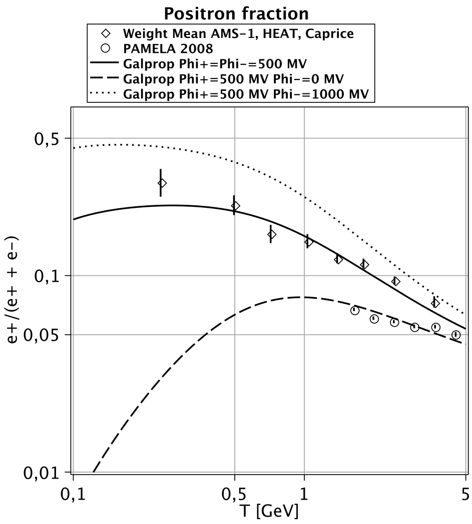

Fig. 1. The positron fraction measured during the A+ period (AMS, CAPRICE & HEAT) compared to the positron fraction measured during the A- period (PAMELA). The prediction from GALPROP is shown modulated with various modulation parameters Φ for electrons and positrons.

I. INTRODUCTION

The concept of charge-sign dependent solar modulation has been well established in theoretical models of the heliosphere (e.g. [1]) and can be easily verified using the magnetic field model suggested by Parker[2]. Experimental evidence for charge-sign dependent solar modulation has been collected with space-borne experiments (e.g. ISEE/ICE 3[3], IMP-8[4], ULYSSES[5]) as well as a few balloon-borne experiments (e.g. AESOP[6], BESS[7]). The Proton Electron Radiation Detector Aix-la-Chapelle (PERDaix) presented in this paper will measure the cosmic protons, positrons and electrons in the energy range between 0.5 GeV and 5 GeV with the goal of measuring the charge-sign dependent solar modulation of electrons during the solar minimum of the $A-$ period. Similar measurements have been previously performed by the AESOP experiment.

A better understanding of charge-sign dependent solar modulation will help interpreting the recently published PAMELA[8] positron fraction (figure 1). This measurement shows a positron excess at high energies compared to the prediction of pure secondary positron production by GALPROP[9]. At energies below $5\,\mathrm{GeV}$ the positron fraction is lower than the prediction that fitted measurements during the A+ period of the solar cycle. Using the simple force-field approximation[10] to describe solar modulation with independent modulation parameters $\Phi+$ and $\Phi-$ for positively and negatively charged particles, this deviation can be described as suggested by Gast[11].

The PERDaix experiment is designed, built and conducted by undergraduate and graduate students supported by the Physics AC-Ib department of the RWTH Aachen University and applies for a balloon flight within the scope of the BEXUS (Balloon-borne Experiments for University Students) program.

BEXUS is an outreach program of the Swedish National Space Board (SNSB) and the German Aerospace Center (DLR) for university students offering balloon flights with ZODIAC balloons produced by the French Centre National d'Études Spatiales. The fully inflated balloons have a volume of up to $12000\,\mathrm{m}^3$ and can carry payloads of up to $117\,\mathrm{kg}$ to altitudes of $25-35\,\mathrm{km}$. At these altitudes we expect temperatures below $-40\,°\mathrm{C}$ and pressures of approximately $5\,\mathrm{hPa}$ (see figure 2). The BEXUS balloons are launched from ESRANGE,

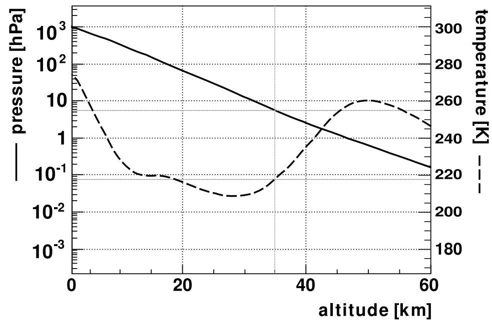

Fig. 2. Temperature and pressure as a function of the altitude for a balloon launch from Kiruna in october according to the NRLMSISE-00 model[12].

Kiruna, Sweden and typically achieve flight durations of 2-5 hours depending on weather conditions.

II. The PERDaix detector

The PERDaix detector is a magnet spectrometer on top of a transition radiation detector. Figure 3 shows a mechanical drawing of the detector and its components.

At the heart of the detector is a hollow cylindrical permanent magnet array (HCPMA) (see figure 4) based on the Halbach design[13]. It has a height of $80\,\mathrm{mm}$, an outer radius of $104.6\,\mathrm{mm}$ and an inner radius of $75.9\,\mathrm{mm}$. Its total weight is approximately $9\,\mathrm{kg}$. The magnetic field is produced by 72 cylindrical NdFeB magnets with a magnetic remanence of $1.4\,\mathrm{T}$. The magnets are arranged in two rings within a supporting aluminium matrix. The magnets in the inner ring have a diameter of $12\,\mathrm{mm}$ and the magnets in the outer ring have a diameter of $16\,\mathrm{mm}$. The resulting homogeneous magnetic field within the HCPMA is $B = 0.3\,\mathrm{T}$. The NdFeB magnets were donated to the PERDaix project by Vacuumschmelze[14].

The tracking detector surrounding the magnet is based on thin scintillating fibers read out by linear silicon photomultiplier arrays. The tracker is modular and consists of twenty $32\,\mathrm{mm}$ wide and $300\,\mathrm{mm}$ long double-sided modules with five layers of $0.24\,\mathrm{mm}$ thin scintillating fibers on either side of the module and silicon photomultiplier arrays mounted on one end while the other end is covered by a mirror to increase light collection. The modules are arranged in four layers providing eight position measurements with a spatial resolution of $0.075\,\mathrm{mm}$ each.The two inner layers above and below the magnet have a small stereo angle of $100\,\mathrm{mrad}$ with respect to the bending plane allowing the measurement of particle coordinates in the non-bending plane with a resolution of approximately $1\,\mathrm{mm}$. The tracker design is based on the much larger PEBS scintillating fiber tracker[15] which is being built at RWTH Aachen University, allowing the re-use of the same technology for PERDaix.

The momentum is measured by calculating the angle of deflection by the permanent magnet. Such an angle-angle measurement results in a relative momentum resolution of

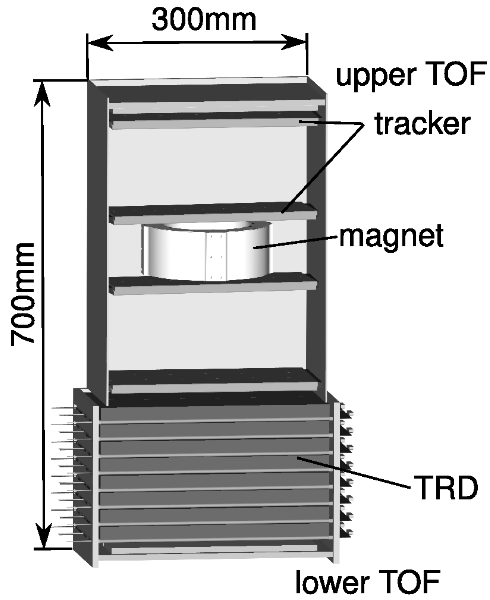

Fig. 3. A 3D model of the PERDaix detector.

$$\frac{\sigma_p}{p} = p/GeV * 10.5\% \oplus 17\%$$

which corresponds to a maximal detectable rigidity of $9.36\,\mathrm{GV}$.

The transition radiation detector (TRD) is based on the design of the AMS-02 transition radiation detector[16] which was also built at RWTH Aachen University. It consists of eight layers of straw tubes of $0.072\,\mathrm{mm}$ thin multilayer aluminium-capton foil with an inner diameter of $6\,\mathrm{mm}$ filled with an $80/20$ Xe/CO_2 mixture. On top of each layer of straw tubes a $20\,\mathrm{mm}$ thick layer of irregular fleece radiator is placed. The PERDaix TRD is for the most part assembled from material left over from the production of the AMS-02 detector. The PERDaix transition radiation detector achieves a proton rejection of approximately 3000 at an electron efficiency of $35\,\%$ and energies greater than $1\,\mathrm{GeV}$. The efficiency of the transition radiation process quickly approaches zero for the production of detectable X-ray photons below a Lorentz factor $\gamma \approx 1000$ (energies of $0.5\,\mathrm{GeV}$ for electrons).

The trigger is provided by a time-of-flight detector (TOF) consisting of $10\,\mathrm{mm}$ thick and $20\,\mathrm{mm}$ wide scintillator bars, each read out by a silicon photomultiplier with an active area of $3 \times 3\,\mathrm{mm}^2$. The TOF panels are located on top of the upper-most tracker layer and below the TRD. The TOF aims for a time resolution of approximately $400\,\mathrm{ps}$ helping with the proton rejection at low energies below $1\,\mathrm{GeV}$.

The geometric acceptance of the detector is about $50\,\mathrm{cm}^2\mathrm{sr}$. The detector is designed to have a low weight of approximately $30\,\mathrm{kg}$ (including electronics and batteries for about 10 hours of operation) and a low power consumption $< 50\,\mathrm{W}$. The tracker with its 5120 readout

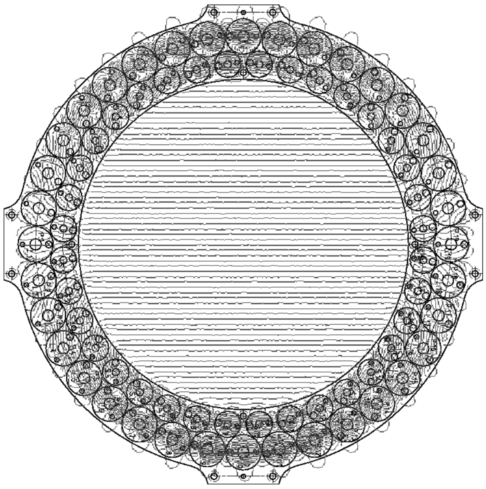

Fig. 4. A mechanical drawing of the PERDaix permanent magnet array with magnetic field lines calculated with the finite element method.

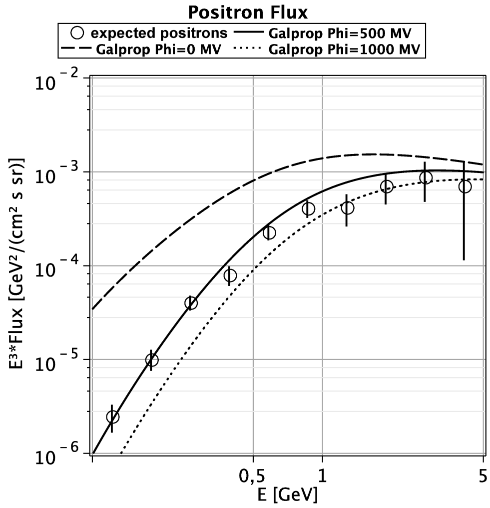

Fig. 5. The expected measurement of primary cosmic positron spectrum for a solar modulation constant $\Phi = 500\,\mathrm{MV}$. Atmospheric backgrounds are not included.

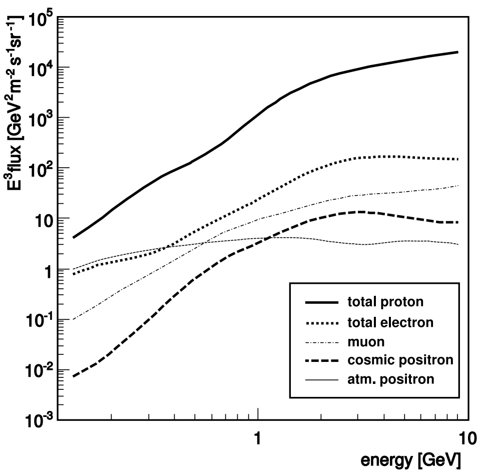

Fig. 6. The expected particle fluxes calculated by PLANETOCOSMICS for $5\,\mathrm{hPa}$ residual pressure or an altitude of approximately $37\,\mathrm{km}$.

channels has the largest power requirement contributing $20\,\mathrm{W}$ including readout electronics. The PERDaix detector will not be placed in a pressurized container, therefore all components, including the gas system for the TRD and the high voltage power supply have to be designed to operate at extremely low temperatures and near vacuum pressure.

III. MEASURING THE SOLAR MODULATION WITH PERDAIX

The PERDaix geometrical acceptance of $50\,\mathrm{cm}^2\mathrm{sr}$ allows measuring cosmic electron spectra despite the short flight duration expected from the BEXUS flight.

Accounting for solar modulation with an estimated modulation parameter $\Phi = 500\,\mathrm{MV}$ and a geomagnetic cutoff rigidity of approximately $500\,\mathrm{MV}$ (see also [18]), a total of about 100 cosmic positrons, 700 cosmic electrons and 60000 cosmic protons can be expected in the rigidity range of $0.5\,\mathrm{GV}$ to $5\,\mathrm{GV}$ in 2 hours.

The background of atmospheric positrons and electrons depends on the altitude and has been studied extensively using the PLANETOCOSMICS[17] tools. The expected dominant particle fluxes for a measurement at altitudes of $37\,\mathrm{km}$ ($5\,\mathrm{g/cm}^2$ residual atmosphere) is shown in figure 6. The dominant backgrounds are of course protons, electrons and positrons from interactions in the residual atmosphere. At low energies of $0.5 - 5\,\mathrm{GeV}$ the proton flux is 50-1000 times higher than the positron flux. A sufficient proton suppression up to a few GeV can be achieved by the TRD which offers a proton rejection of 3000 at an electron efficiency of 0.35. At this electron efficiency the positron flux can measured up to about $3\,\mathrm{GeV}$ in two hours (figure 5). The electron background is sufficiently suppressed by the charge-sign measurement of the spectrometer to up to about $5\,\mathrm{GeV}$. Muons and pions are also suppressed by the TRD. However, the expected irreducible background of atmospheric positrons makes accurate measurements of the primary positron flux below $1\,\mathrm{GeV}$ difficult. All other backgrounds are suppressed to the 10% level.

The electron measurement (figure 7) is far less problematic since the primary negative electron flux is almost a magnitude larger compared to that of positrons. As a result, the solar modulation parameter for electrons Φ_{e^-} can be measured sufficiently well.

The backgrounds for the proton measurement are well below 10% even at altitudes without relying on the TRD for particle identification, allowing an easy measurement of the modulation parameter Φ_p in the proton sector (figure 8).

With a measurement time of only two hours, PERDaix remains highly sensitive to the short-term variability of cosmic rays due to solar coronal mass ejections or Forbush decreases. Solar events can modulate the cosmic ray fluxes at $1\,\mathrm{GeV}$ by more than one magnitude whereas the effect of solar modulation results in changes in the cosmic ray flux of a few tens of percent at this

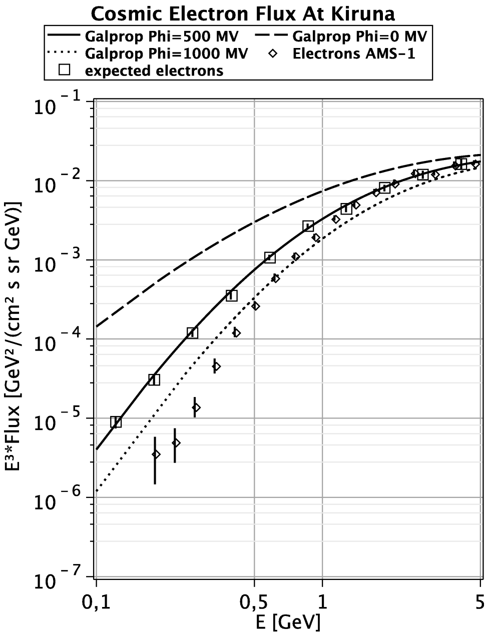

Fig. 7. The expected measurement of the primary cosmic electron spectrum for a two hour flight. The error bars indicate the statistical uncertainty of the measurement.

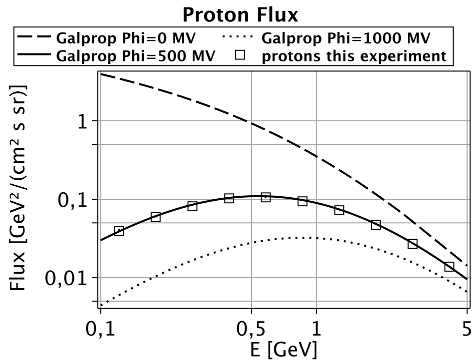

Fig. 8. The expected measurement of the cosmic protons for a solar modulation constant of $\Phi = 500\,\mathrm{MV}$.

energy. A measurement in autumn 2010 would be near the end of the current solar minimum. The solar activity around the time of the measurement will have to be taken into account.

IV. CONCLUSION

The PERDaix detector has the capability of fitting the solar modulation parameter Φ independently to proton, electron and positron spectra. This offers an important insight into the charge-sign dependent solar modulation for electrons that can be compared to the measurements recently published by the PAMELA experiment and help understand if indeed the low positron fraction at around $2\,\mathrm{GV}$ measured by PAMELA can be explained by charge-sign dependent solar modulation alone.

The second objective of PERDaix is to test a detector concept that will be used for the PEBS[19] experiment, parts of which are currently being produced in Aachen.

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